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TITLE: PARTICLE PHYSICS CANDIDATES FOR THE COSMION SOLUTION TO THE SOLAR NEUTRINO PROBLEM

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PARTICLE PHYSICS CANDIDATES FOR THE COSMION SOLUTION TO THE SOLAR NEUTRINO PROBLEM

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Abstract

We discuss several particle physics candidates for the cosmion solution to the solar neutrino problem. We outline their properties and methods of detecting them.

I INTRODUCTION

We shall assume in this talk that the following tenets are valid. The many arguments, both pro and con, have been discussed at length in this workshop:

- There exists dark matter and the ratio of dark to luminous mass, $M_{dark}/M_{lum} \approx 10$.
- This dark matter is <u>not</u> baryonic.
- The dark matter is in the form of a weakly interacting massive *elementary* particle.

In this introduction we emphasize that the hypothesis of an elementary particle form of dark matter is delightfully testable. Consider the following three methods of detection, the details of which have been fully discussed by the previous speakers:

i) <u>Direct detection</u>

Germanium detectors [Ahlen et. al., Caldwell et. al.] have been used to detect the neutral current interactions of galactic halo dark matter candidates. It is expected that a flux of order

[1] Talk presented at the Recontres de Moriond, Les Arcs, Savoie, France, March 6-13, 1988.

$\left(\frac{m_z}{m_x}\right) \times 10^7 cm^{-2} sec^{-1}$, where m_x is the mass of the dark matter particle, is incident on these detectors located deep underground. Neutral current collisions of the dark matter with the Germanium nuclei kick electrons into the conduction band yielding, when sufficient energy is released, an observable signal. The experiments are thus threshold limited. As discussed by Caldwell, in this workshop, the upper limit on the mass m_x of any dark matter candidate, with spin-independent interactions of order $10^{-38} cm^2$, is $m_x \leq 15$Gev. The sensitivity on the WIMP– nuclear cross-section is such that as σ_{xN} increases above $10^{-38} cm^2$ the upper limit on m_x approaches 10 Gev. Future detectors with silicon, used with either semiconductor technology, bolometer technology or with new technology to detect ballistic phonons are under development. It is believed that in the near future the interesting range $4 \leq m_x \leq 10$ Gev will be accessible.

ii) Indirect detection

WIMPs which make up the galactic halo are captured by the sun. If they can annihilate, they will. Generically, they produce e, μ or τ neutrinos with energy $E_\nu = m_x$. These neutrinos are a visible background in detectors designed to look for nucleon decay. Limits discussed at this workshop from Kamiokande, which fold in some theoretical assumptions to be discussed shortly are given below. The following mass ranges [in Gev] are excluded at 90% CL:

Dirac neutrino [zero cosmic asymmetry] — $10 < m < 20$, $60 < m$

Majorana neutrino — $65 < m$

Supersymmetric partners of neutrinos

electron sneutrino — $3 < m < 25$

muon sneutrino — $3 < m$

tau sneutrino — $4 < m < 25$

Photino - higgsino limits are too complicated to reproduce here. They depend on the masses of the SUSY scalars which are exchanged in scattering and annihilation processes. A range of parameters, in the two dimensional space of photino-higgsino mass vs. SUSY scalar mass, can be excluded.

Dirac and Majorana neutrinos are assumed to interact via Z^0 exchange only. In the case of Dirac neutrinos, which can have a conserved particle number, zero cosmic asymmetry is assumed. If a non-zero cosmic asymmetry is assumed then the limits become weaker and for a particular value of the asymmetry, of order the known baryon asymmetry, the limits disappear altogether.

In all cases it is assumed that the ratio of the dark matter energy density ρ_{DM} to the critical energy density

$$\rho_c = \frac{3 H_0^2}{8 \pi G} \simeq 2 \times 10^{-29} g/cm^3;$$

$\Omega_{DM} = \frac{\rho_{DM}}{\rho_c} = 1$. In the case of sneutrinos, photinos or higgsinos, the value of Ω_{DM} is used to fix the value of some of the unknown parameters in the theory. The annihilation cross-sections are determined by the unknown masses and couplings of the particles exchanged (see fig. 1). If Ω_{DM} is taken to be smaller, then one would need larger annihilation cross-sections. This in turn would generically imply larger capture cross-sections in the sun for the dark matter candidates. As a result the annihilation rates in the sun would rise and the limits would become more stringent. Thus assuming $\Omega_{DM}=1$ for SUSY particles gives conservative limits on their mass.

iii) Production in High Energy Accelerators

Elementary particle dark matter candidates have the great virtue of being producible in high energy accelerators. For example, a monojet seen at a $p\bar{p}$ collider, such as Fermilab, could be a signal for photinos (see fig. 2). Such high energy experiments could provide us with significant information on the identity of the dark matter.

II SOLAR NEUTRINO PROBLEM [SNP]

The SNP expresses the mismatch between experimental observation and theoretical prediction. An experiment begun in 1964 by R. Davis designed to detect electron neutrinos from the sun via their charge exchange reaction with ^{37}CL has observed 2.1 $\pm$ .3 (1σ) SNU, where 1SNU $\equiv$ one capture per 10^{36} target atoms per second. The ν_e's which can be observed in this experiment come predominantly from the high energy tail ($\geq$ 1 Mev) of a side chain in the pp cycle (see fig. 3). They result from the beta decay of $^8B \longrightarrow ^8Be^* + e + \nu_e$ with maximum energy $E_{\nu_e} \approx$ 14 Mev. The theoretical expectation for the Davis experiment is 7.9 $\pm$ 2.6 (3 σ) SNU [Bahcall and Ulrich] with 77% of the signal due to ^8B decay. Future experiments using Gallium as a target will be more sensitive to the pp cycle (the dominant energy source in the sun). A Russian-Los Alamos-Univ. of Pennsylvania collaboration located at Baksan should be taking data by the end of 1988 with 60 tons of Gallium, while a German, French, Italian collaboration, known as Gallex, should have 30 tons of Gallium ready to start taking data in 1990. We should note that Kamiokande has seen a signal of ν_e's from the sun which is consistent with, and thus confirms, the Davis result.

There are a number of theoretical explanations for the discrepancy between theory and experiment, which can be fit into two distinct categories.

A) Revision of some poorly understood properties of the sun which are an integral component of the so-called Standard Model of the Sun. The observed properties of the sun are its total luminosity, radius, mass, and surface abundance of elements. These are inputs into solar calculations which then provide as output details of the interior of the sun. However some details of the solar interior are insensitive to the input parameters. One such detail is the temperature at the core of the sun. For example, lowering the core temperature, T_c, by as little as 12 % would solve the solar neutrino problem, as it presently exists with regard to the ^8B neutrinos, but would hardly affect the solar luminosity.

B) One could revise the expected properties of neutrinos so that on the way to the earth their numbers are depleted. This can be due to decay or oscillation into some other type which would not be observed in the Davis experiment. For example, with the MSW effect [Mikheyev, Smirnov and Wolfenstein] an electron neutrino with mass of order 10^{-2} ev could oscillate into a muon neutrino on its way out of the sun. The ν_μ would not interact via charge exchange in the chlorine.

In this talk we will focus on the first possibility. In particular we emphasize that the number of ^8B neutrinos is extremely sensitive to T_c. 95% of the ^8B neutrino producing region of the sun lies within a radius $R \leq .08\,R_\odot$ or includes a mass fraction $M \leq .05 M_\odot$ where the temperatures are high enough to produce the ^8B. This is to be compared to the pp neutrino producing region which extends out to .2 $R_\odot$ or $M \leq .35\ M_\odot$.

III COSMIONS

The cosmion solution to the SNP relies on these facts for its success [Faulkner and Gilliland, Spergel and Press]. The cosmion is a WIMP which sits near the center of the sun and isothermalizes the core via its long mean free path. The mass and cross-section of the cosmion are fixed by the requirements that T_c is lowered by about 12% without affecting the temperature beyond $M \sim .05\ M_\odot$ where most of the solar luminosity originates. The results of detailed calculations follow:

i) Cosmions are stable, $\tau_x \geq 10^8 \tau_0$ where τ_0 is the present age of the universe. They must be in the sun now to solve the SNP. Moreover, their decay products, such as e^+ would be visible in the cosmic ray spectrum, thus requiring $\tau_x/\tau_0 \gg 1$ [Raphaeli].

ii) The cosmion mass satisfies $\sim 4 \leq m_x \leq\sim 8\,Gev$. Cosmions with mass less than ~ 4 would evaporate out of the sun. Cosmions which are too heavy do not occupy a large enough core region.

iii) The effectiv mion scattering cross-section in the sun is $\sigma_{x\odot} \sim 4 \times 10^{-36} cm^2 \equiv \sigma_c$, with an abundance mber $N_x \sim 10^{-11}$. $\sigma_c \equiv \frac{m_x}{M_\odot} R_\odot^2$ is the critical value of the cross-section defined roug by the condition that every cosmion which traverses the sun scatters at least once. This value of $\sigma_{x\odot}$ and N_x is <u>optimal</u> in the sense that either an increase or decrease in $\sigma_{x\odot}$ would require an increase in N_x to solve the SNP. If $\sigma_{x\odot}$ is decreased then the cosmion scatters less often; on the other hand, if $\sigma_{x\odot}$ increases, the cosmion mean free path decreases making it difficult to transport the heat far enough. In either case more cosmions are needed to do the thermal transport.

iv) The cosmion annihilation cross-section must be small so that the necessary abundance N_x can be achieved. This requires $\sigma_a \leq 10^{-4} \sigma_{x\odot}$.

v) Finally one wonders how do cosmions get in the sun in the first place. Note they have all the right properties to be cold dark matter candidates. If one assumes that cosmions provide the missing mass which constitutes our galactic halo, then one can calculate the number of cosmions which have been captured by the sun throughout its lifetime. Calculations give

$$N_x \sim 6 \times 10^{-9} \left[\left(\frac{\sigma_{x\odot}}{\sigma_c} \right), 1 \right] \left(\frac{m_p}{m_x} \right) \left(\frac{v_e}{\bar{v}_x} \right) \left(\frac{\rho_x}{M_\odot / pc^3} \right),$$

where [,] means use the smaller of the two numbers, $v_e \sim 600\ Km/s$ is the escape velocity from the surface of the sun, and $\bar{v}$ and ρ are the mean velocity and energy density of cosmions in the solar neighborhood. Using typical values $m_x = 6\, m_p$, $\sigma_{x\odot} = \sigma_c/2$, $\bar{v}_x = 300$ Km/s and $\rho_x = .01\, M_\odot/(pc)^3 \sim \frac{1}{3} Gev/cm^3$ we obtain $N_x \sim 10^{-11}$. We emphasize that we obtained an abundance N_x which is <u>consistent</u> with $\sigma_{x\odot}$ according to (iii). Note if we decrease $\sigma_{x\odot}$ by an order of magnitude, we obtain $N_x \sim 10^{-12}$ but we would need according to (iii) $N_x \sim 10^{-10}$ to solve the SNP. Thus this numerical coincidence is a remarkable success for the cosmion model. Indeed, cosmions can simultaneously provide a solution to both the missing mass and solar neutrino problems [Press and Spergel, Krauss, Blumenthal].

IV COLD DARK MATTER CANDIDATES

Do the standard cold dark matter candidates (massive neutrinos, photinos, higgsinos, sneutrinos, axions) have the right properties to be cosmions? This question was addressed by Krauss, Freese, Spergel and Press and the answer was unequivocally -- no. The problem is twofold:

1) The elastic scattering cross-sections are too small; and/or

2) the annihilation cross-sections are too large.

Axions are simply too light. As an example of the other candidates, consider a massive neutrino. In this case, the ratio of the scattering cross-section to the critical cross-section satisfies $\frac{\sigma_{sc}}{\sigma_c} \sim 10^{-3} - 10^{-2}$ where the first number is for $\nu - p$ scattering and the second is for coherent $\nu - {}^4He$ scattering. Whereas, the typical annihilation cross-section for a massive neutrino satisfies $\sigma_a \sim 4 \times 10^{-36} cm^2$.

Thus the standard cold dark matter candidates cannot solve the SNP. Moreover light neutrinos, which have been proposed to solve the SNP via neutrino oscillations, are typically too light to be the dark matter. We thus conclude that cosmions are the only elementary particles which can simultaneously solve both problems.

V COSMION CANDIDATES

In this section we shall describe some proposed cosmion candidates. It is important to note that, although all the candidates satisfy the necessary criteria to be cosmions, many of their detailed dynamical properties differ. In particular, the nature of their coherent scattering off of heavy nuclei can differ. This will result in different limits on their mass from both direct and indirect methods of detection. It will also affect their influence on stellar evolution. Let us consider the Gelmini-Hall-Lin classification of cosmions which we believe is complete. There are three possible cases which differ in the way the annihilation problem is overcome. In all three cases the cosmion scattering cross-section $\sigma_{x\odot}$ must be enhanced.

1) The cosmion has <u>no</u> conserved particle number – the annihilation cross-section σ_a must be suppressed.

2) The cosmion has a conserved particle number, and there are an equal number of cosmions and anti-cosmions in the universe. If the cosmion capture cross-section in the sun is larger than that for anti-cosmions, then N_x will be mostly cosmions and the conserved particle number will prevent them from annihilating.

3) Cosmions have a conserved particle number and there is a cosmic asymmetry of cosmions. As a result the sun, as well as the universe, will have more cosmions than anti-cosmions. The conserved particle number will again prevent them from annihilating.

V.1 NO CONSERVED PARTICLE NUMBER– σ_a SUPPRESSED

If x is the neutral component of a weak isodoublet, it will annihilate via s-channel Z^0 exchange. This cross-section is too large ;typically $\sigma_a \approx G_F^2 m_x^2$. For the special case of a Majorana fermion, the annihilation cross-section has an approximate p-wave suppression and we have $\sigma_a \approx \sum_f G_F^2(m_f^2 + \beta^2 m_x^2)$ where β is the relative velocity of the annihilating cosmions and the sum is over all fermions f in the final state with mass $m_f < m_x$. However, in the mass range of interest the tau always contributes to the sum and the cross-section is still too large. Thus the Z^0 coupling must be avoided which implies that x is an electroweak singlet, the neutral component of a triplet or a higher integral representation of SU(2) weak. x can now annihilate via s-channel scalar exchange or t-channel scalar (fermion) exchange for x a fermion (boson), where the final states are assumed to be fermionic. The case of s-channel scalar exchange is forbidden by SU(2)xU(1) conservation for any known quark or lepton in the final state. We are thus uniquely lead to consider t-channel exchange (fig.4a). Since the same new couplings must also allow for the scattering cross-section (fig.4b) we must have quarks in the final state and thus we conclude that the scalar which is exchanged is a color triplet. Finally in order to benefit from a p-wave suppression, we take x to be a Majorana fermion which couples only to light quarks u and d. The scattering cross-section , in the non-relativistic approximation, is of order $\sigma_{sc} \approx \frac{g^4 m_N^2 m_x^2}{4\pi m_\phi^4 (m_N + m_x)^2}$ where g is the coupling constant , m_N is the target mass and m_ϕ is the color triplet scalar mass. Given g$\approx$ 1 and $m_\phi \approx$ 75 Gev , the scattering cross-section is of order σ_c as needed. This is the model proposed by GHL.

V.2 CONSERVED PARTICLE NUMBER—NO COSMIC ASYMMETRY

In this case one requires the scattering cross-section of the cosmion to be larger than that of the anti-cosmion. The annihilation cross-section need not be suppressed. The model proposed by GHL requires a color triplet, mixed scalar–pseudo-scalar, ϕ with x a neutral Dirac fermion. The scalar component dominates in the cosmion scattering graph (fig. 5a), while the pseudo-scalar component dominates in the anti-cosmion scattering graph (fig. 5b). In order for these two contributions to differ and at the same time to be consistent with SU(2)xU(1) conservation, ϕ must be a mixture of a weak doublet and singlet. Once again the scattering cross-section will be of order σ_c for g$\approx$ 1 and $m_\phi \approx 75$ Gev.

An alternate possibility in this case is for x to be the neutral component of an electroweak doublet and to invoke the t-channel exchange of a new Z' gauge boson and a scalar doublet (fig. 6) whose couplings and mass are fine-tuned so that the coherent interference causes the cross-section for cosmion scattering to be significantly enhanced over that of anti-cosmion scattering.

V.3 CONSERVED PARTICLE NUMBER AND A COSMIC ASYMMETRY

In this case, four proposals have been made. In each case x is a neutral Dirac fermion. The cases are distinguished by the particles exchanged in the cosmion–quark scattering amplitude (see fig.7).

1. Color triplet scalar exchange — Gelmini, Hall and Lin
2. Z' exchange — Ross and Segrè
3. Photon exchange — Raby and West a
4. Higgs exchange — Raby and West b

VI EXPERIMENTAL SIGNATURES

Case 1 is by now familiar. The characteristic property of this model, valid for all three versions, is that the color triplet scalar couples the cosmion to light quarks only. In the first version this is necessary to suppress the annihilation cross-section, in subsequent versions it is necessary to avoid problems with flavor changing interactions (see fig. 8). In all three versions, the cosmion can be produced at $p\bar{p}$ colliders. The signature would be mono- and di-jets (fig. 9).

Case 2 requires a new gauge boson Z' with mass of order 65 Gev which couples to quarks but not to leptons; otherwise it would have already been detected in $p\bar{p}$ colliders. This model deserves further study to see whether it is consistent with all known data.

Case 3 has been studied in great detail. There are two distinct versions of this model. In both versions, the magnino **m** (the name given the cosmion in this model) has an anomalous magnetic moment resulting from well defined one loop contributions. The model also requires a new light scalar doublet. It is this anomalous magnetic moment of order $10^{-2} \times \frac{e\hbar}{2m_m c}$ which allows the magnino to couple to photons and to obtain a large enough scattering cross-section on protons. The two versions of the model are distinguished by the electroweak quantum numbers of the magnino.

In the first version, the magnino is the neutral component of an electroweak doublet i.e. a fourth generation massive Dirac neutrino. Its charged partner (a heavy charged lepton m$^-$) necessarily has mass of order m_m. This is necessary for two reasons. The first reason is theoretical; if m$^-$ is much heavier than m , the anomalous magnetic moment is suppressed by factors of order $\left(\frac{m_m}{m_{m^-}}\right)^2$ which would suppress the scattering cross-section. As a result, m and m$^-$ must be nearly degenerate. The second reason is experimental; there have been many searches for heavy sequential charged leptons and the latest limits from AMY at TRISTAN now rule out a charged lepton with mass less than 27.4 Gev ,while the limits from UA rule out a charged lepton with mass less than 41 Gev. In both cases it is explicitly assume that the neutrino partner of the charged lepton is massless. Recently D. Stoker and M. Perl from MARK II and L. Mathis from TPC have re-analyzed existing PEP data to look for a nearly degenerate heavy lepton doublet. They have not seen any evidence for such leptons and they thus constrain the mass difference of the charged and neutral lepton to satisfy $\sim$ 200 Mev $\leq (m_{m^-} - m_m) \leq\sim$ 400 Mev for $m_{m^-} \geq\sim$ 4 Gev.

In the second version of the model, the magnino is an electroweak singlet which couples predominantly to τ and ν_τ. In this case, the magnino does not have a charged partner and would only be visible in ASP (Anamolous Single Photon) type e$^+$ e$^-$ experiments.

Case 4 by far requires the least amount of new physics. In this model, the cosmion is the neutral member of a fourth generation of neutrinos. The dominant contribution to ν_x– nucleus scattering is from Higgs exchange. The Higgs mass is fixed by requiring a large enough scattering cross-section $\sigma_{\nu_x N}$ where

$$\sigma_{\nu_x N} = \frac{m_N^2 m_{\nu_x}^2}{\pi(m_N + m_{\nu_x})^2 m_h^4}\left(\frac{2n_H}{27}\sqrt{2}G_F m_N m_{\nu_x}\right)^2$$

where N is the target nucleus, ν_x is the cosmion, h is the light Higgs and n_H is the number of heavy quarks (including c, b, t, $\cdots$). We find

$$\sigma_{\nu_x proton} \approx 1.5 \times 10^{-36} \left[\frac{\left(\frac{n_H}{5}\right)^2 \left(\frac{m_{\nu_x}}{4 Gev}\right)^2}{\left(\frac{m_h}{400\, Mev}\right)^4} \right] cm^2 .$$

Using the fact that ν_x scatters coherently on heavy nuclei and that there is $\approx$ 10% Helium in the sun we can obtain a large enough $\sigma_{x\odot}$ with a Higgs with mass of order 700 Mev [2].

Since we require a light Higgs, it is necessary to consider the experimental limits on such a particle. The lower limit on the Higgs mass $m_h >\sim 14$ Mev comes from observing the decay of excited states of Helium -4. P. Franzini, this workshop, has discussed several processes which can, in principle, be used to place better limits on the Higgs mass. For example, with improved limits on the branching ratios for $K \rightarrow \pi + h$ or $B \rightarrow h + anything$, with the subsequent decay $h \rightarrow \mu^+ \mu^-$, a light Higgs in the relevant mass range could be detected. He also presented new results from CUSB II on Upsilon decay to h + photon which apparently rule out a Higgs with mass 600 Mev $< m_h <$ 5 Gev at 90% CL. These results rely on the theoretical calculation of the decay rate, including order α_s corrections [Vysotsky, Nason]. It is important to recognize that the order α_s correction is 84% of the tree level result, i.e.

$$\Gamma(\Upsilon \rightarrow h + \gamma) = \Gamma_{Wilczek} \times \left[1 - \left(\frac{4\alpha_s}{3\pi}\right) a_H(z)\right]$$

where $z \equiv 1 - \frac{m_h^2}{m_\Upsilon^2} \approx 1, a_H(1) = 7 + 6\,ln(2) - \frac{\pi^2}{8} \approx 10$ and for $\alpha_s = .2$ we obtain $\Gamma(\Upsilon \rightarrow h + \gamma) = \Gamma_{Wilczek} \times [1 - .84]$. With such a large radiative correction , we must consider the theoretical expectation for this decay rate as suspect. Hence, we conclude, more theoretical work is necessary before one can rule out a light Higgs using this process.

VII REFERENCES

Ahlen, S.P., et.al. , 1986, Phys. Rev. Lett. .

Bahcall, J.N. and Ulrich, R.K., 1987, Rev. of Mod. Phys.

Blumenthal, G., unpublished.

Caldwell, D.O., et.al., 1987, UCSB preprint UCSB-HEP-87-13; also Caldwell,

[2] This estimate neglects the fact that the Helium distribution in the sun is different than the Hydrogen distribution which affects the capture and heat transport calculations.

this workshop

Davis, R., Jr., 1964, Phys. Rev. Lett. 12, 303.

Faulkner, J. and Gilliland, R.L., 1985, Ap. J. 299, 994.

Gilliland, R.L., Faulkner,J., Press,W.H. and Spergel, D.N., 1986, Ap. J. 306, 703.

Gelmini, G.B., Hall, L.J., Lin, M.J., 1987, Nucl. Phys. B281, 726.

Krauss, L.M., 1985, Harvard preprint, HUTP-85/A008a, unpublished.

Krauss, L.M., Freese, K., Spergel, D.N. and Press, W.H., 1985, Ap.J. 299, 1001.

Mathis, L., 1987, Proceedings of the International Symposium on Lepton and Photon Interactions at High Energies, DESY, Hamburg.

Mikheyev, S.P. and Smirnov, A.Yu., 1986, Nuovo Cim. 9C, 17.

Nason, P., 1986, Phys. Lett. B175, 223.

Press, W.H. and Spergel, D.N., 1985, Ap. J. 296, 679.

Raby, S. and West, G.B., 1987a, Nucl. Phys. B292, 793; Phys. Lett. B194, 557.

Raby, S. and West, G.B., 1988b, Phys. Lett. B202, 47.

Raphaeli, Y., private communication.

Ross, G.G. and Segrè, G.C., 1987, Phys. Lett. B197, 45.

Spergel, D.N. and Press, W.H., 1985, Ap. J. 294, 563.

Stoker, D. and Perl, M., 1987, The Standard Model, The Supernova 1987A, edited by J. Tran Thanh Van, Editions Frontières, p. 445.

Vysotsky, M.I., 1980, Phys. Lett. B97, 159.

Wilczek, F., 1977, Phys. Rev. Lett. 39, 1304.

Wolfenstein, L., 1978, Phys. Rev. D17, 2369; 1979, ibid. D20, 2634.

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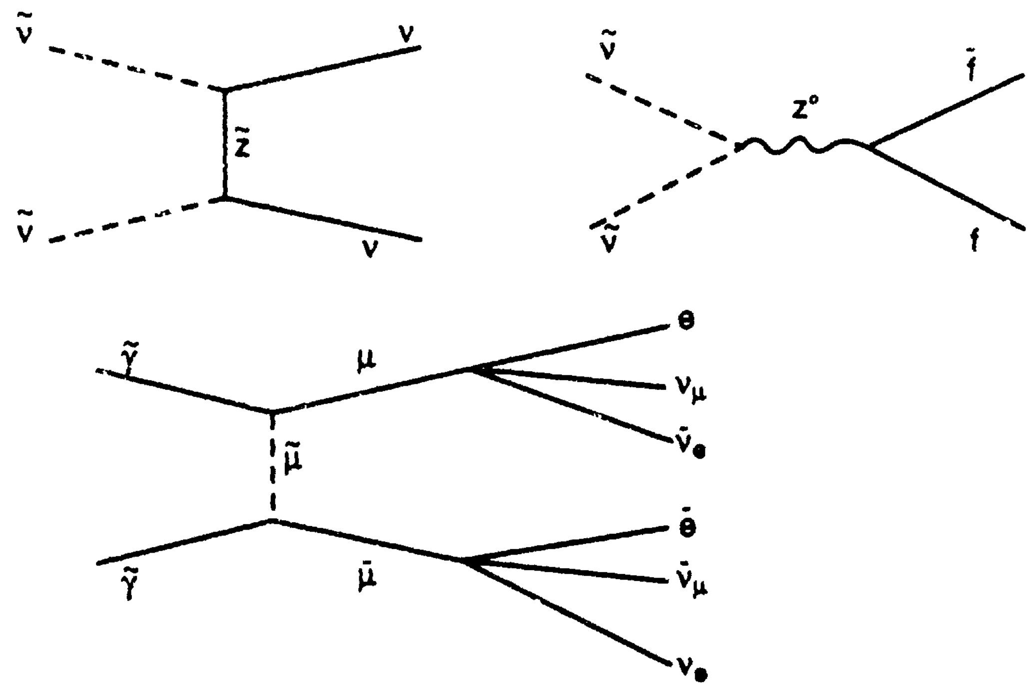

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fig.2

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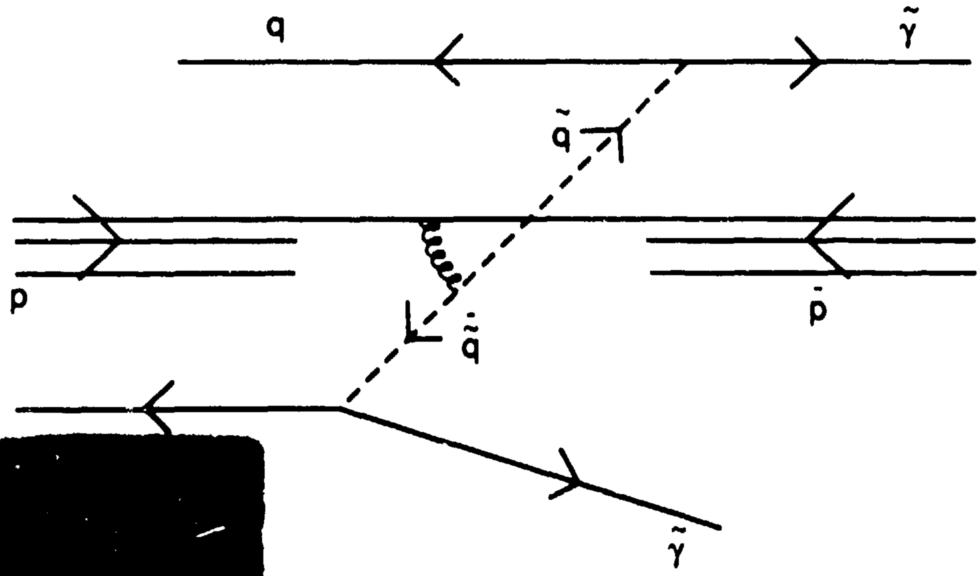

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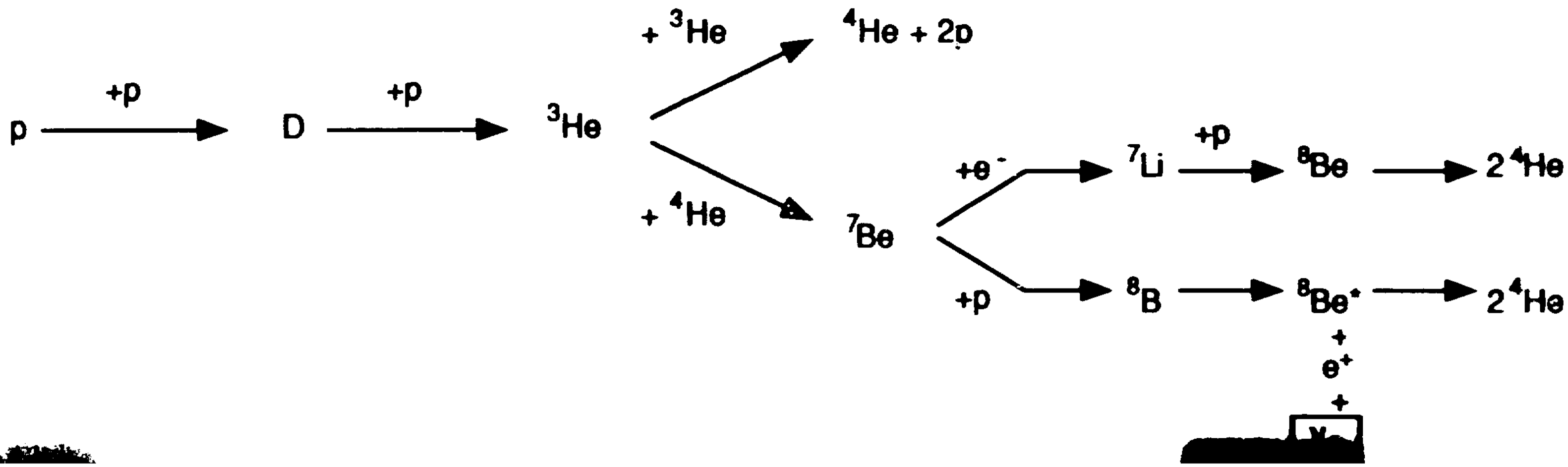
Fig.3



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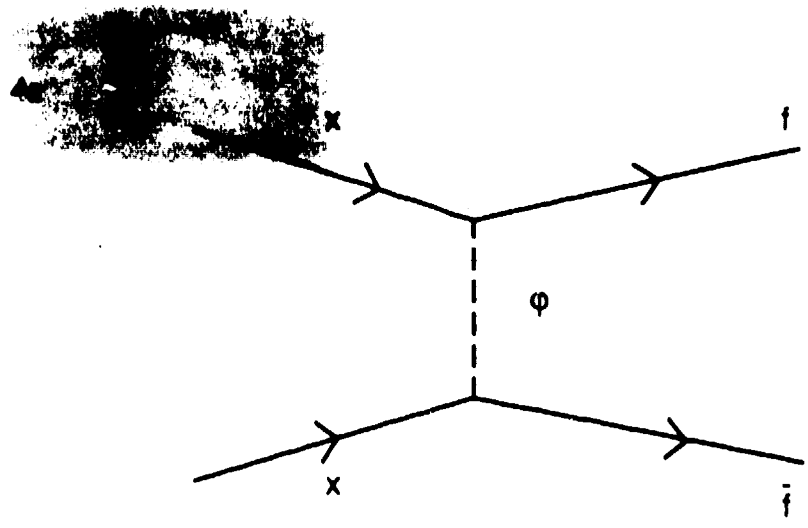

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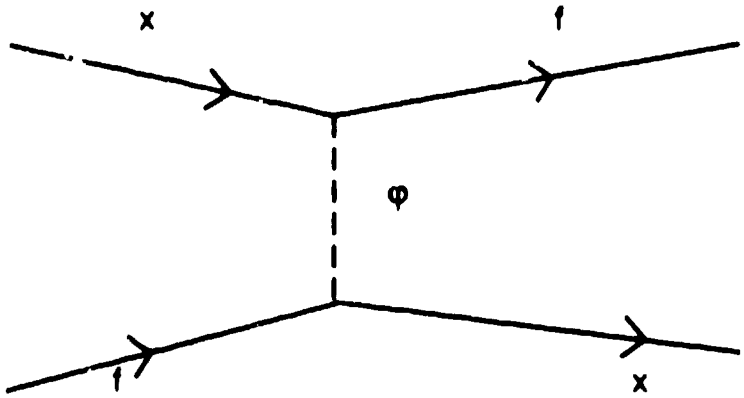

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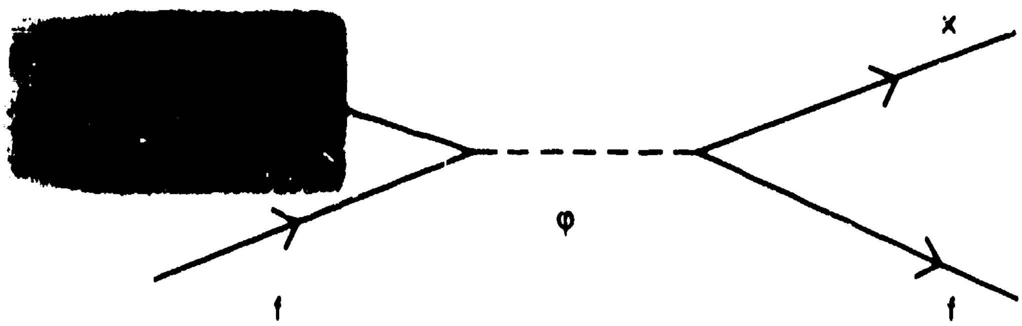

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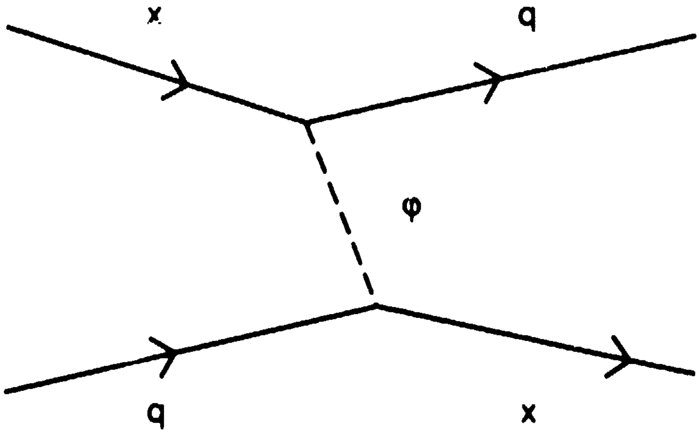

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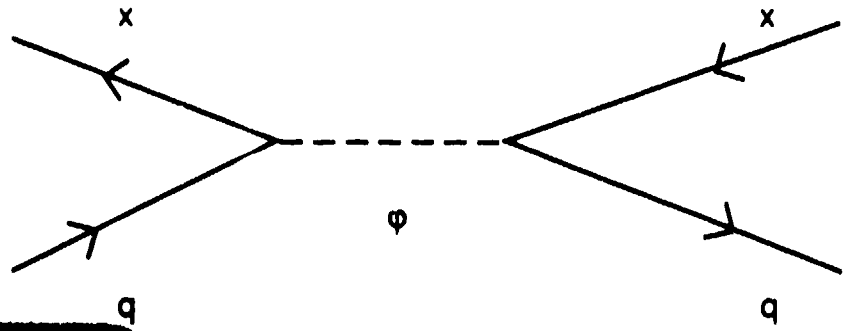

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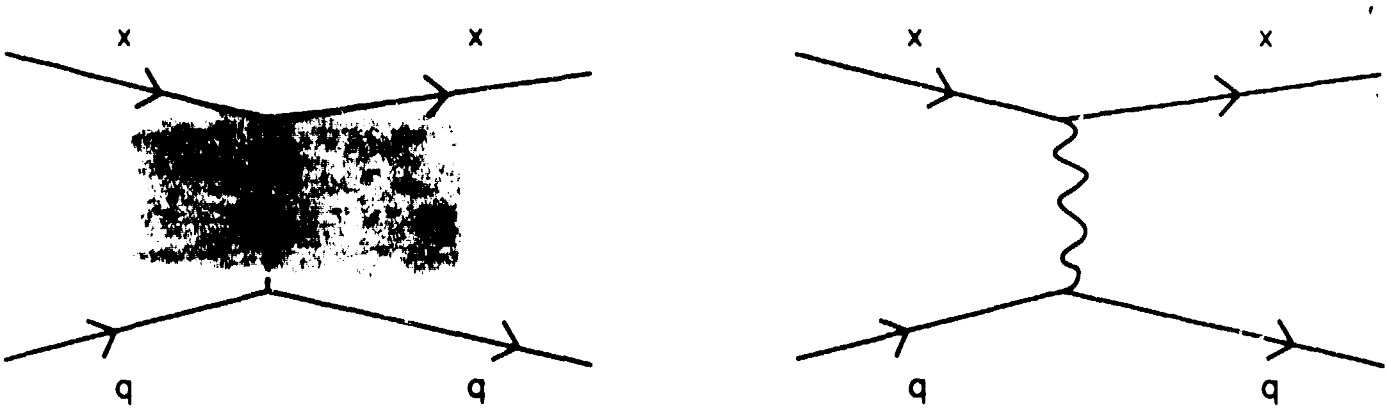
fig.6



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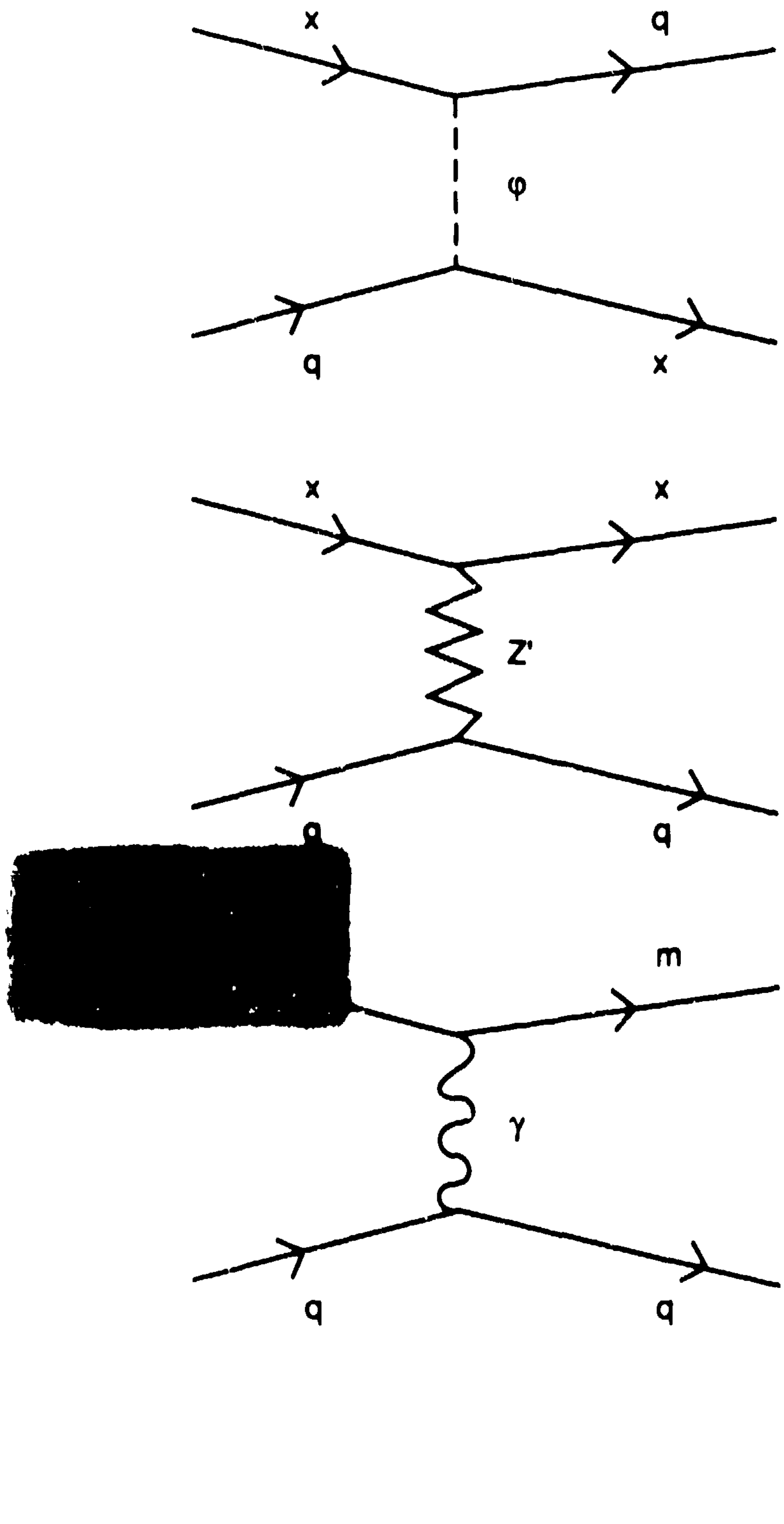

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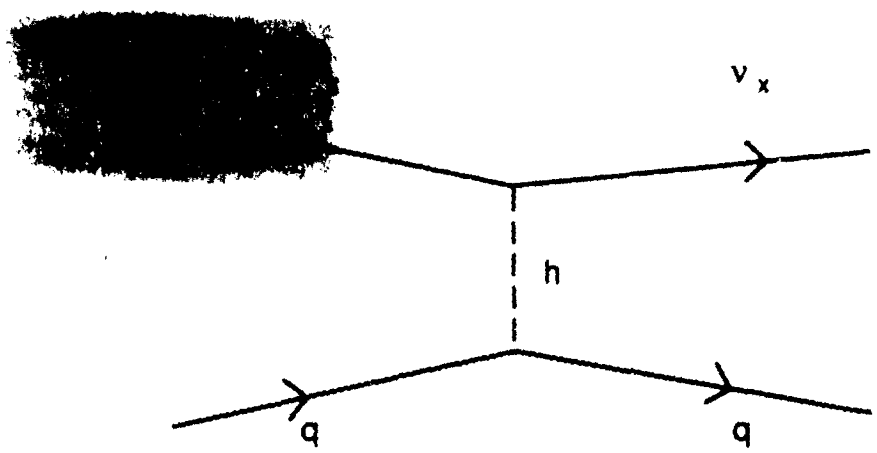
fig.7



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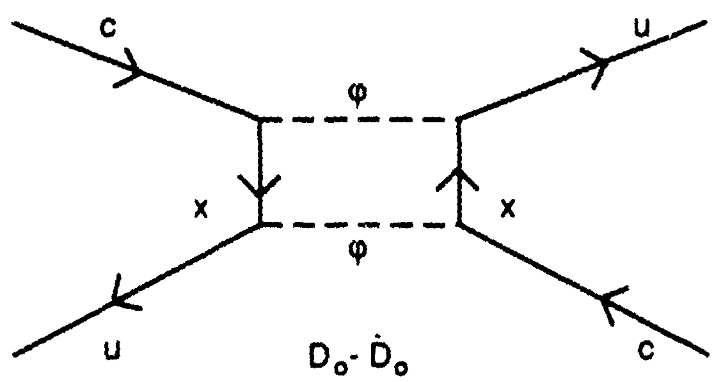

t87
fig.9